The Environmental Assessment of Biomass Waste Conversion to Sustainable Energy in the Agricultural Biogas Plant

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Abstract Operating an agricultural biogas plants offers the potential of stable, clean, renewable and diversified energy source. It is also a good opportunity to reduce the amount of organic waste. The objective of this study is to evaluate the main environmental hot spots of operating agricultural biogas plants using LCA methodology. This article presents the environmental impact assessment of two agricultural biogas plants with different type of feedstock provision. The environmental life cycle assessment was carried out from “cradle to gate” using the SimaPro software and the ILCD 2011 Midpoint+ methodology. The boundaries of the system included cultivation of maize, delivery of feedstock to the plant, energy production, storage and transport of digestate. The results show that transport of liquid manure induces the highest environmental impact.

1 Introduction

In 2019, the European Parliament assigned the resolution on the climate and environment emergency. Based on that, it is an urgent need to implement and develop many new technologies especially in energy sector, to prevent the further intensification of the crisis and reduce the global temperature growth.

It was expected that carbon dioxide produced by human activity would be absorbed by the oceans. Meanwhile, by warming the atmosphere, CO₂ is additionally released from the oceans and melting ice, so that its concentration may increase exponentially and cause more and more negative climatic phenomena. Food production and consumption account for as much as 35% of all greenhouse gases in the atmosphere, of which agriculture alone accounts for 10%.

Developed countries are struggling with ever-increasing amounts of waste, including the agri-food industry waste, due to overproduction and consumption of food. The issue of the generation of biodegradable waste is often marginalized, while animal production and the generated livestock manure contribute to 30% of

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the total emission of anthropogenic methane to the atmosphere. The global warming potential for methane is from 23, which means that the same amount of methane in the atmosphere as CO₂ will have a 23 more significant impact on climate warming. Technologies based on anaerobic digestion are very useful in reducing the amount of waste from agri-food industry and at the same time enable controlled methane capture and energy production in cogeneration systems.

Manure is a livestock residue that has little commercial value [1]. The slurry digestate which is a result of the anaerobic fermentation can be used as more bio-available fertilizer form [2] and helps to reduce the number of pathogens entering the soil with direct application. Furthermore, storing animal manure in the open air results in methane and carbon dioxide emissions through the process of self-remediation [3]. Anaerobic digestion of animal manure reduces the environmental impacts caused by carbon dioxide, methane and nitrous oxide emissions from storage and reduces waste and odours [4]. For example, in Finland case, anaerobic fermentation on cattle farms contributes to the reduction at approximately 9% of the national agricultural GHG emission reduction goal during the 2005–2020 period [5].

However, animal manure has low biogas yield (9–36 m³/Mg) compared with different feedstock especially maize silage. In this case, the co-digestion of different biodegradable substrates is often used at farms. The most effective in producing biogas is digesting liquid manure with maize silage, what is however economically unfavourable, and what even worse, maize cultivation for the energy production purpose stays against cultivation for feeding. The solution could be co-digestion with different waste from agri-food production. Such products have often relatively higher methane yield than manure, e.g. potato pulp or fruit pomace. Very favourable to use as a feedstock is also distillery waste. The methane yield for that waste is lower and similar to liquid manure but to manage with this waste is also very problematic and biogas plant can be a solution.

Anaerobic digestion seems to be a very efficient way to close the material and nutrient loop according to EU circular economy paradigm. The field application of digestate is also a part of nutrients' circularity. Digestated materials have advantages for their use as soil amendments which are microbial stability, hygiene and high amount of N present as ammonium. It improves also the total organic C concentration in soil [6, 7].

Biogas is a promising substitute for natural gas of fossil origin [8]. Published articles about environmental impact of biogas production analysed heat and energy production [9], biomethane purification [10] and domestic use [11]. Reviews also describe biogas LCA from manure in a global perspective, technological studies of biogas production and specific studies for specific countries or region. Studies also concern a transport of feedstock and indicate that it can play an important role in the environmental performance of biogas production [12]. The maximum transportation distance should not extend 10 km to make biogas environmentally viable for small-scale plants [9, 13], and for large-scale plants, it should be within 64 km [14]. However, mostly studies focus on electricity generation from biogas than on the possibility of biomass waste treatment.

The aim of this paper is to present the results of selected two biogas plants, which mostly differ with the type of feedstock, the way it is transported and the transportation distance, in order to highlight the most critical factors (hot spots) from the environmental point of view of operating those installations whose main purpose is the waste treatment.

2 Materials and Methods

The life cycle assessment (LCA) methodology was chosen for this study based on ISO 14040 and ISO 14044 as the most comprehensive evaluation of environmental impact. LCA analysis includes four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of results [15, 16]. In this work, the ILCD 2011 Midpoint+ v.1.10 method was considered. The ILCD was developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in cooperation with the Environment DG which is widely used in Europe. In this method, 16 very detailed impact assessment categories are distinguished [17]. The inventory data for this study were taken directly from tested agricultural biogas plants located in Poland and from the ecoinvent database v. 3.3 and processed using the SimaPro calculation program.

Selected biogas plants were assessed in details from gate-to-gate perspective. Input data were collected for separate unit processes implemented under the modern mesophilic fermentation technology: maize cultivation, feedstock delivery, energy production and digestate storage and transport. All results were analysed relative to the reference unit, which is named as a functional unit (FU) and defined as “a delivery of 1000 Mg of feedstock designed to biogas conversion”. The values of the eco-indicator were presented in impact categories, expressing the value of impact at environmental ecopoints (marked with the Pt symbol).

The allocation cut-off by classification model was used in this study, and the primary production of input of raw materials and pig slurry was allocated to the primary user/producer. It was also considered that the main product is electricity with 100% allocation, but the main purpose of those plants is the biomass waste management. Only the maize cultivation was taken into consideration as a dedicated tillage.

Two agricultural biogas plants A and B were taken into consideration with installed power 1.0 MW and 0.526 MW, respectively. In both cases, slurry digestate is not separated and used as a natural fertilizer on arable fields. The most important parameters of the tested plants are collected in Table 1. The construction and demolition of the biogas plant as well as the production of biomass waste feedstock and digestate application on fields were excluded from the scope of the study. The environmental impacts of the electricity production from biogas based on anaerobic co-digestion of pig slurry, silage maize and different feedstock from agri-food industry were determined (Table 2).

Table 1 The most important parameters of the tested biogas plants

Parameter	Biogas plant A	Biogas plant B
The amount of biogas [m ³ /year]	4,169,760	1,725,155
The amount of electricity produced [MWh/ year]	786.1	300.7
The amount of heat produced [MWh/ year]	776.9	319.3
The amount of heat used [MWh/ year]	147.0	222.1
The amount of digestate [m ³ /year]	35,515	19,744
Total efficiency [%]	51	69

Table 2 The feedstock input in relation to annual operations

Biogas plant	Type of feedstock	The amount of feedstock [Mg/year]	Biogas yield [m ³ /Mg]	Maximum transport distance [km]
A	Pig slurry	14,824.0	232.0	5.0
	Maize silage	21,693.0	36.0	1.0
B	Maize silage	2,025.0	230.0	45.0
	Distillery residues	11,489.7	31.0	Gravity pipeline
	Carrot pomace	1,595.9	76.0	11.3
	Potato pomace	5,919.6	94.0	22.5
	Pig slurry	590.0	9.0	3.8
	Protein sediments	402.6	700.0	172.5

Liquid animal manure was transported by a farm tractor with a barrel. Maize harvested from the fields was transported to a biogas plant using heavy wheeled transport. The remaining raw materials from the agri-food industry were transported with a trailer or with different types of lorries. Only distillery residues in biogas plant B were delivered by a gravity pipeline.

3 Results and Discussion

The results were estimated by using the ILCD 2011+ method and the 16 midpoint categories. The results were described on two different levels of LCA methodology: characterization and weighting for four-unit processes – maize cultivation, feedstock delivery, energy production and digestate storage and transport. The feedstock delivery includes transport of agri-food residues, maize ensilaging on-site and delivery to the digester. In analysed biogas plants, we can distinguish six types of transport: (1) road transport of pig slurry to the plant, (2) road transport of raw materials to the plant, (3) pipeline transport to the plant, (4) internal transport on-site, (5) maize transport from the field and (6) digestate transport for final use as fertilizer.

The cumulative environmental impact of biogas plant B (1.48 kPt) is significantly lower than that of biogas plant A (42.66 kPt). The liquid feedstock with low

organic mass content and biogas yield in plant B are provided by gravity pipeline. In an installation A, a feedstock is delivered by a tractor with a barrel (Table 3). The highest environmental burdens of biogas plant A stem from the delivery of a feedstock, whereas of plant B, it is related to the storage and transport of the digestate.

The highest value of eco-indicator for plant B concerns the digestate storage and transport. In this case, the transport of liquid digestate takes place using a tractor with a barrel. The storage of the digestate itself does not involve any energy consumption or emissions to the atmosphere. The digestate is stored in a sealed container, so transport in this process is the main contributor. Moreover, the fields for the application of the digestate are located in the vicinity of biogas plant B and the distance is 0.9616 km maximum. The transportation distance of a digestate to biogas plant A is almost twice longer (1,606 km), which can significantly affect the higher environmental impact. The area required for the spreading of the digestate and the maximum transportation distance were calculated as follows [18].

Biogas plant A exhibits a significant impact on almost all categories; however, the contribution of all categories for both biogas plants is almost equal (Table 4).

Only for the water resource depletion category for both biogas plants, the value is below zero. It means that in this category, the environmental impact can be positive. The lower is the value, the more positive is the impact. The reason for obtaining such results for this impact category is the temporary storage of the liquid digestate. It may provide a reservoir of water for field irrigation just next to the fertilization purpose.

Based on the results, three leading groups of factors with the highest environmental impact were separated: transport, electricity consumption and others. The factors were classified in terms of the value of environmental burdens and significance for the impact on climate change. In both biogas plants, transport is the main contributor and represents 99.9% and 98.1% of the total cumulative impact value, respectively (Fig. 1). Even electricity consumption, which in both cases comes from the grid, represents a negligible part of the total impact, 0.03% and 1.56%, respectively (Fig. 1).

Comparing all different types of transport as it was mentioned earlier in this article, for biogas plant A, the highest environmental impact is related to the transport of pig slurry (91%), while for biogas plant B, the impact mainly stems from the transport of the digestate (87%) (Fig. 2). The transport of raw materials to biogas plant B is characterized by a relatively low environmental impact, even though the distance from the production site to the biogas plant is up to 100 km. Raw materials from agri-food industry such as fruits and vegetable pomace have a higher organic mass content and a higher biogas yield per unit weight (Table 2). Then the

Table 3 The cumulative eco-indicator values for individual stages of operation

Biogas plant	Maize cultivation [kPt]	Feedstock delivery [kPt]	Energy production [kPt]	Digestate storage and transport [kPt]
A	0.58	38.68	0.01	3.39
B	0.01	0.18	0.02	1.27

Table 4 LCIA results of each biogas plant on the characterization level

Impact category	Unit	Plant A	Plant B
Climate change	kg CO ₂ eq	1.93E+07	957E+05
Ozone depletion	kg CFC – 11 eq	2.30E+00	134E-01
Human toxicity, non-cancer effects	CTUh	5.82E+01	1.85E+00
Human toxicity, cancer effects	CTUh	2.12E+00	7.84E-02
Particulate matter	kg PM2.5 eq	1.82E+04	7.31E+02
Ionizing radiation HH	kBq U235 eq	1.26E+06	6.50E+04
Ionizing radiation E (interim)	CTUe	6.65E+00	3.67E-01
Photochemical ozone formation	kg NMVOC eq	1.59E+05	6.70E+03
Acidification	molc H ⁺ eq	1.61E+05	6.86E+03
Terrestrial eutrophication	molc N eq	5.56E+05	2.36E+04
Freshwater eutrophication	kg P eq	5.93E+03	2.47E+02
Marine eutrophication	kg N eq	5.11E+04	2.17E+03
Freshwater ecotoxicity	CTUe	3.02E+08	1.14E+07
Land use	kg C deficit	1.35E+08	5.37E+06
Water resource depletion	m ³ water eq	–1.94E+06	–5.85E+04
Mineral, fossil and ren resource depletion	kg Sb eq	3.27E+03	1.27E+02

Fig. 1 The contribution of main critical factors in total environmental impact

transportation can be significantly extended obtaining the same results compared with the distance for pig slurry. In plant B, the distillery residues were transported by gravity pipeline what leads to negligible environmental impact at the exploitation stage. The impact can be visible at the construction or demolition stage when the input of metal used for pipelines is taken into account. However, in this study, these two stages were omitted.

Fig. 2 The share of different types of transport in feedstock delivery process: (a) biogas plant A, (b) biogas plant B

4 Conclusions

The production of renewable energy from biogas is an unquestionably effective way to replace energy from conventional sources and reduce negative environmental impact and climate change. Biogas plants can also provide a solution to the problem of managing many agricultural and agri-food industry waste. However, taking into account many previous studies and this work, we can conclude that transport is the main contributor of the cumulative environmental impact of operating an agricultural biogas plant. Liquid raw materials with a low biogas yield should be transported by pipelines, and biogas plants using this type of raw materials should be located in the vicinity of feedstock sources. This is also confirmed by Cherubini et al. who claimed that keeping animals close to biogas plant provide the reduction of the environmental impact [19].

In the case of the ferment, the distance over which it is to be extracted should be limited or other solutions should be used to limit the quantity of the ferment that is needed to be used, e.g. by drying. The environmental impact of drying processes and the possible pelletization of the resulting biomass should be studied.

Undoubtedly, biomass waste is a key source of renewable energy (not only a bio-gas), but we have to be aware of the possible environmental impact.

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